Science of the Total Environment 666 (2019) 147–154

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Estimation of work-related injury and economic burden attributable to heat stress in Guangzhou, China

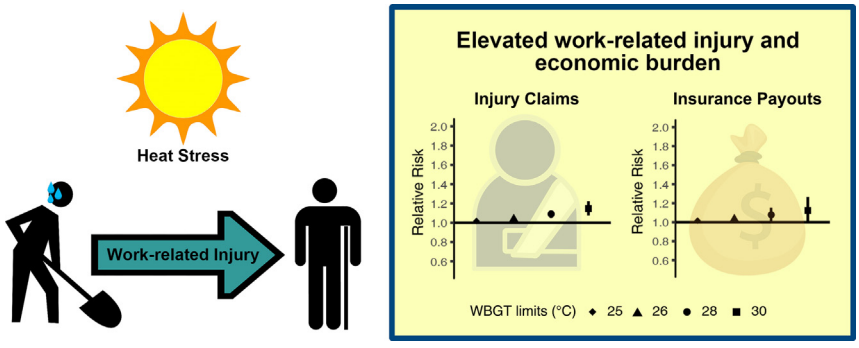
Rui Ma [a,1], Shuang Zhong [b,1], Marco Morabito [c,d], Shakoor Hajat [e], Zhiwei Xu [a], Yiling He [a], Junzhe Bao [a], Rongrong Sheng [a], Changchang Li [a], Chuandong Fu [f,*], Cunrui Huang [a,**]

[a] School of Public Health, Sun Yat-sen University, Guangzhou, China
[b] Center for Chinese Public Administration Research, School of Government, Sun Yat-sen University, Guangzhou, China
[c] Institute of Biometeorology, National Research Council, Florence, Italy
[d] Centre of Bioclimatology, University of Florence, Florence, Italy
[e] Department of Public Health, Environments and Society, London School of Hygiene & Tropical Medicine, London, UK
[f] Guangdong Provincial Work Injury Rehabilitation Hospital, Guangzhou, China

HIGHLIGHTS

- High WBGT contributed to increased risks of work injuries.
- Substantial costs were attributable to heat stress due to excessive injury claims.
- Workers in small enterprises and with low educational attainment were most affected.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 15 November 2018
Received in revised form 30 January 2019
Accepted 13 February 2019
Available online 14 February 2019

Editor: SCOTT SHERIDAN

Keywords:
Climate change
Heat stress
Occupational health
Work-related injury
Economic cost

ABSTRACT

Background: Climate change has exacerbated the health effects of high ambient temperatures on occupational health and safety; however, to what extent heat stress can induce workplace injuries and economic costs is poorly studied. This study aimed to quantify the attributable fractions of injury claims and subsequent insurance payouts using data from work-related injury insurance system in Guangzhou, China.
Methods: Individual workers' injury claims data were collected for the period of 2011–2012, including demographic characteristics and work-related information. Daily maximum wet bulb globe temperature (WBGT, °C) was calculated from meteorological data. To examine the association between WBGT index and work-related injury, we fit a quasi-Poisson regression with distributed lag non-linear model. Then we calculated the numbers of injury claims and costs of insurance compensations attributable to days with WBGT above the heat stress limit according to the national occupational health standards.
Results: There were 9550 work-related injury claims, resulting in an insurance payout of 282.3 million Chinese Yuan. The risks of injury claims increased with rising WBGT. 4.8% (95% eCI: 2.9%–6.9%) of work-related injuries and 4.1% (95% eCI: 0.2%–7.7%) of work-related injury insurance payouts were attributed to heat exposure for WBGT threshold above the heat stress limit. Male workers, those in small enterprises and with low educational attainment were especially sensitive to the effects of heat exposure.

* Correspondence to: C. Fu, Guangdong Provincial Work Injury Rehabilitation Hospital, Guangzhou 510440, China.
** Correspondence to: C. Huang, School of Public Health, Sun Yat-sen University, Zhongshan Road #2, Guangzhou 510080, China.
E-mail addresses: fucd168168@163.com (C. Fu), huangcr@mail.sysu.edu.cn (C. Huang).
[1] These authors contributed equally to this work.

https://doi.org/10.1016/j.scitotenv.2019.02.201
0048-9697/© 2019 Elsevier B.V. All rights reserved.

Conclusions: Heat stress can contribute to higher risk of work-related injury and substantial economic costs. Quantified the impacts of injuries and related economic costs should be considered to develop targeted preventive measures in the context of climate change.

© 2019 Elsevier B.V. All rights reserved.

1. Introduction

As our climate continues to warm (IPCC, 2018), heat-related health burdens are expected to rise. A large number of epidemiological studies demonstrated that high temperatures increase both mortality and morbidity (Huang et al., 2012; Li et al., 2015; Odame et al., 2018; Ye et al., 2012; Yu et al., 2012), and these relationships are often applied to climate projection data to estimate future health burdens (Huang et al., 2011). However, a big unknown is the degree to which current relationships will still hold once ambient temperatures begin to surpass levels that general populations are currently exposed to and limits to adaptability are potentially reached (Kjellstrom et al., 2016). Studies from occupational health settings can offer insight into such patterns since exposures to heat are often far higher (Schulte et al., 2016).

As physiology-based studies show, dissipation of internal generated heat during strenuous activity is vital to human health (Smith and Johnson, 2016; Vanos et al., 2010), and heat exposure from the ambient environment can exacerbate heat stress among those constantly exposed such as outdoor workers (Sheng et al., 2018). With accumulation of heat stress, core body temperature can exceed the safe and acceptable thermal limits of 37 °C, not only leading to acute health issues, such as heat exhaustion and heat stroke, but also increasing risks of work-related injury and occupational diseases (Kjellstrom, 2016; Mairiaux and Malchaire, 1985; Pilcher et al., 2002). Impaired workers' health may also lead to limited working capacity, resulting in productivity and economic loss. It is estimated that heat-related work absenteeism and performance reduction can result in an economic loss equivalent to 6.2 billion US Dollars (USD) for the Australian workforce, which is about from 0.33 to 0.47% of its GDP (Zander et al., 2015). Xia et al. (2018) also found that the severe heat waves of 2013 in Nanjing caused a total of 27.5 billion Chinese Yuan (CNY) of economic losses, equating to 3.4% of the city's gross value of production.

Previous studies have observed significant effects of heat exposure on work-related injuries in Adelaide, Australia (Xiang et al., 2014c), Tuscany, Italy (Morabito et al., 2006), and Quebec, Canada (Adam-Poupart et al., 2015). Sheng et al. (2018) found that both hot days and warm nights increased work-related injury risks in China. Additionally, Martinez-Solanas et al. (2018) quantified non-optimal ambient temperature related injuries and associated economic burden in Spain, showing that heat posed more danger than cold in occupational settings. Xiang et al. (2018) found significant increase in medical costs and work-days lost due to occupational heat-induced illness. Although the health impacts of ambient heat exposure on work-related injury is of growing interest, there is little research focusing on the economic loss of high temperatures because of injury (Martinez-Solanas et al., 2018; Xiang et al., 2018). Furthermore, where losses are quantified, these are mainly based on estimated economic costs and burdens rather than actual costs (Martinez-Solanas et al., 2018), thus introducing considerable uncertainty.

As the Earth's climate continues to change and workers will be exposed to ever-increasing ambient temperatures, it is crucial to evaluate variations in heat-related health impacts and economic losses in occupational health settings; so that governments can develop targeted labor protection policies to protect health and reduce the productivity loss. In this study, we aim to quantify the impact of heat stress on work-related injury claims, also assessing subsequent economic costs in one of the most populous cities in southern China.

2. Materials and methods

2.1. Study setting

Guangzhou is one of the biggest cities in China, and one of the major manufacturing centers in the world. With a population of >14 million and a labor force of 8.35 million in 2016, the GDP of Guangzhou reached 2150 billion CNY in 2017 (330 billion USD), ranking fourth in all Chinese cities. Located in a sub-tropical monsoon climate region, Guangzhou usually experiences long summer with high temperatures and abundant rainfall. The monthly average temperatures are above 28 °C (the monthly average maximum temperature is even higher than 33 °C) during July and August. In these months, the monthly mean values of relative humidity are close to 80%. This situation often contributes to creating average thermal conditions during summer months characterized by moderate and strong heat stress.

2.2. Work-related injuries data

In this study, we used a retrospective study design. We obtained de-identified worker injury claim data of Guangzhou from the work-related injury insurance system, referred to the period January 1, 2011 to December 31, 2012. This data includes demographic characteristics (age, gender, and educational attainment) and work-related information (enterprise name, size and industry type), the date of injury occurrence, the assessment of injury severity and the total amount of insurance payouts. The daily insurance payouts were then calculated by aggregating amounts of individual payouts, and also showed as USD with the exchange rate of December 31, 2012 (1 CNY = 0.16 USD). Educational attainment was categorized into three levels: low education (middle school and below, which is a compulsory education); intermediate education (high school or higher vocational college), and high education (university or postgraduate education). Injured workers were diagnosed for their gradation of disability with national standard "*Standard for identify work ability – Gradation of disability caused by work-related injuries and occupational diseases*" (GB/T 16180-2006) issued by Ministry of Labor and Social Security, China (MoLSS, 2006) and were classified into eleven degrees. Then they were categorized into three groups of injury severity according to the functionality of each degree: 1) the minor injury group, including people who did not take the impairment identification or those whose disability did not reach the mildest class; 2) the medium injured group, including people who were classified as degree 10 (the mildest class of disability, their physical function did not lead to permanent damage); and 3) the severely injured group, including people whose identification conclusion were degree 9 to degree 1 (the most serious degree of disability, they suffered from the injury and had permanent dysfunction).

2.3. Weather data

Daily maximum wet bulb globe temperature (WBGT) values were obtained for the city of Guangzhou by using the Hothaps-Soft (High occupational temperature health and productivity suppression) database and software, provided by ClimateSoft Ltd. (Otto et al., 2014). This software obtains meteorological data from NOAA/GSOD (US National Oceanographic and Atmospheric Administration/Global Surface Summary of the Day) and calculates the indoors or full shade WBGT index with the method introduced by Bernard and Pourmoghani (1999).

The WBGT (unit = °C) is a well-established heat stress index that considers the combination of several important microclimate variables useful for heat-stress assessment, such as the natural wet-bulb temperature (T_{nwb}, °C, that represents the largest component of WBGT), the black globe temperature (T_g, °C) and the dry-bulb temperature (T_a, °C). Today, the WBGT represents the most commonly used heat stress index for workplace applications (Kjellstrom et al., 2015; Takakura et al., 2017; Xiang et al., 2014a) and is also used in international standards (ISO, 2017).

Despite its wide usage in international heat stress standards and occupational research, WBGT index is still not a meteorological indicator routinely measured. However, several calculation methods using regular meteorological data have been published (Bernard and Pourmoghani, 1999; Lemke and Kjellstrom, 2012; Liljegren et al., 2008).

2.4. Statistical analysis

All individual claims were transformed into daily time-series data, and grouped by their demographic characteristics, and then merged with meteorological data. A quasi-Poisson regression allowing for over-dispersion with distributed lag non-linear model (DLNM) (Gasparrini et al., 2010) was applied to examine the association between heat stress (WBGT values) and work-related injuries. This approach allows for considering the over-dispersed Poisson distribution of injuries, also accounting for the non-linear association, typical in this kind of investigations, and the potential delayed effect of heat stress. The same approach was used to model the association between heat exposure (WBGT values) and insurance payouts.

The analyses were conducted using the *dlnm* package (2.3.2) (Gasparrini, 2011) in R 3.4.0 (R Core Team, 2018).

The median value of daily maximum WBGT during the whole study period (24 °C) was used as the reference threshold (centering value) for fitting the exposure-response relationship. Then relative risks at 30 °C were reported. We modeled the exposure-response curve with a natural cubic spline with two internal knots placed at equal spaces. The maximum WBGT index was included in the model as cross-basis function. A natural cubic spline of time was used to control for time trend and seasonality and a dummy variable for year was used to adjust for inter-year trends. Other dummy variables for day of the week and public holidays were also fitted in the model.

According to the occupational health standard *Occupational exposure limits for hazardous agents in the workplace* (GBZ 2.2-2007) issued by Ministry of Health of China (MoH, 2007), 8 h full-time work can be conducted safely even for very high work activities when the WBGT at workplace does not exceed 25 °C. For jobs requiring high, moderate and light physical workload, WBGT thresholds of 26 °C, 28 °C and 30 °C, were selected respectively according to the standard. Detailed information was presented in Tables S1 and S2 of Supplemental material.

As the heat-related health effect is generally immediate or occurs on a very short time scale, a time lag of zero day was used in the primary analyses. However, models were also fit by setting maximum time lag periods of 3 and 7 days in the sensitivity analyses to assess possible delayed effects. Other models with different knots and degrees of freedom were also considered in our sensitivity analyses.

To calculate the measures of injury claims and the cost of compensation attributable to high WBGT values, the daily maximum WBGT and the corresponding relative risks were combined to assess the attributable numbers of each day. Finally, the attributable number over the heat stress limit of 25 °C was summed, and 95% empirical confidence intervals (eCI) were provided (Gasparrini and Leone, 2014).

3. Results

Table 1 shows the descriptive statistics for the workers' compensation claims in Guangzhou between 2011 and 2012. In total, 9550 claims occurred during the study period, resulting in an insurance payout of 282.3 million CNY, which equates to 29.6 thousand CNY per injury. About 47%, 28% and 25% of all injuries were classified into the minor, medium and severe injury, respectively. The average insurance payout for severe injuries (72.5 thousand CNY) was higher than for medium injuries (29.4 thousand CNY) and minor injuries (7.1 thousand CNY). There were 4008 injury claims in 2011 and 5542 in 2012, which resulted in an average payout of 33.3 and 26.8 thousand CNY, respectively.

Table 1
Numbers of works' injury claims and insurance payouts during 2011–2012 in Guangzhou, China.

Variables	Injury claims (%)	Insurance payouts (million CNY)
Total	9550 (100)	282.3
Gender		
Male	7377 (77.2)	228.6
Female	2173 (22.8)	53.6
Age group		
<35	4294 (45.0)	116.3
35–44	3327 (34.8)	101
>44	1929 (20.2)	65
Educational attainment		
Low	5378 (56.3)	157.5
Intermediate	3033 (31.8)	91.4
High	1139 (11.9)	33.4
Business size		
Small	5119 (53.6)	158.4
Middle	2908 (30.5)	85.8
Large	1523 (15.9)	38
Injury severity		
Minor	4524 (47.4)	32
Medium	2648 (27.7)	78
Severe	2378 (24.9)	172.4

Note: CNY, Chinese Yuan. 1 Chinese Yuan = 0.16 US Dollar (Exchange rate of December 31, 2012). The business size was categorized according to the Provisions on the Classification Standard for Small and Medium-sized Enterprises (No. 300 [2011]) of the Ministry of Industry and Information Technology, China.

Daily maximum WBGT index ranged from 5.7 °C to 31.3 °C, with a mean value of 22.4 °C and a median value of 24 °C during the 2-year period (Fig. 1). Monthly averaged maximum WBGT was higher than 24 °C during the warm season (May 1–October 31). There were >46% of days (339 days) during which the daily maximum WBGT index exceeded 25 °C (the threshold for reducing working hours during very high labor activities), and 7.5% of days (55 days) during which the maximum WBGT index exceeded 30 °C, that is the threshold for reducing working hours of light workload.

Relative risks (RR) of overall injury claims increased with successive increases in WBGT values, reaching 1.15 at the threshold of 30 °C (95% CI: 1.08–1.22) (Fig. 2). It is estimated that 4.8% of work-related injury claims are attributable to heat exposure above the WBGT threshold of 25 °C (Table 2), corresponding to 461 injuries (95% eCI: 257–658) in the study period. About 11.6 million CNY (95% eCI: 0.6–21.2) used for insurance payouts could be attributed to WBGT values above 25 °C, which represents approximately 4.1% of the total work-related injury insurance payouts during the study period.

High relative risks of work-related injuries and insurance payouts increasing with the WBGT were observed (Figs. 3 and 4). Male (RR: 1.15, 95% CI: 1.1–1.23) and female (RR: 1.14, 95% CI: 1.01–1.29) workers had similar risks of injury with increased the WBGT (Fig. 3), while female only accounted for 22.8% of total injury claims. Among all age groups, workers aged 35 to 44 were most sensitive to the increase of heat stress (RR: 1.16, 95% CI: 1.06–1.28), followed by workers under 35 years old (RR: 1.14, 95% CI: 1.04–1.24) (Fig. 3). On the other hand, the relationship between work-related injuries in workers older than 44 years old was not statistically significant (RR: 1.15, 95% CI: 0.99, 1.32). Workers with intermediate educational attainment showed the highest work-related injury risks with increasing WBGT (RR: 1.19, 95% CI: 1.08–1.32), followed by workers with low educational attainment (RR: 1.14, 95% CI: 1.05–1.23). Though elevated with increasing WBGT,

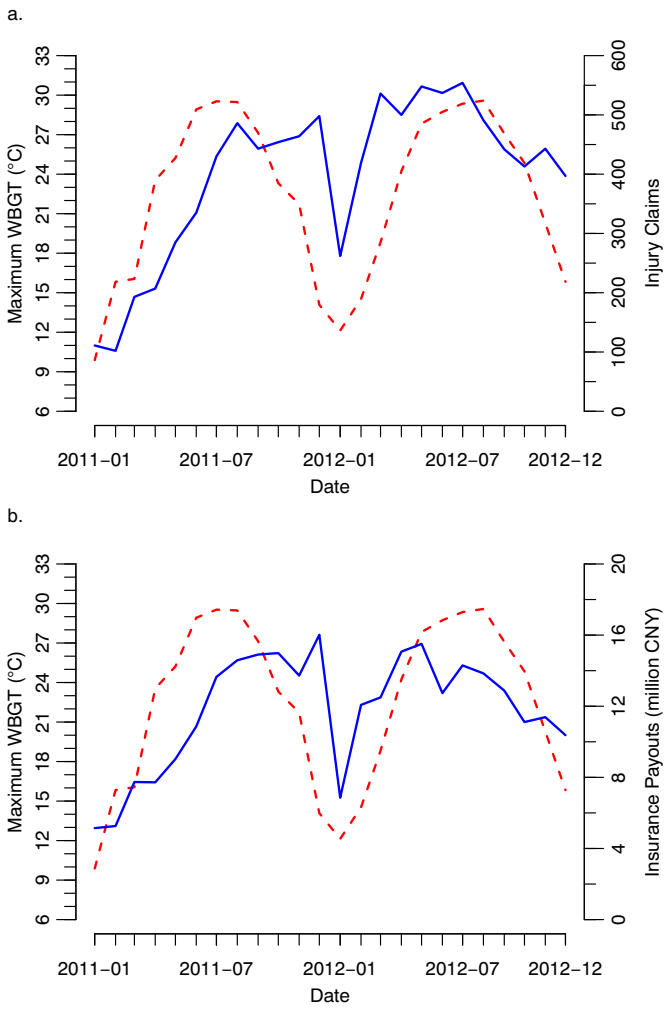


Fig. 1. The time-series of monthly median of maximum WBGT (red dashed line, in both Panel a & b), work-related injury claims (blue solid line, in Panel a), and insurance payouts (blue solid line, in Panel b) during 2011–2012, in Guangzhou, China.

the injury risk of workers with high educational attainment was statistically significant only at a WBGT value of 25 °C (RR: 1.02, 95% CI: 1.00–1.04).

As for business size, workers in small enterprises were most sensitive to the effect of high WBGT thresholds (RR: 1.17, 95% CI: 1.08–1.27), followed by workers employed in medium-sized enterprises (RR: 1.16, 95% CI: 1.04–1.29). No significant associations were found for workers engaged in large enterprises (RR: 1.06, 95% CI: 0.91–1.23) (Fig. 3).

The investigation on different injury severities showed higher risks in the minor injured group (RR: 1.24, 95% CI: 1.14–1.35) (Fig. 3). Significantly increased risks were also observed in severely injured workers, except for the value at the threshold of 30 °C (RR: 1.12, 95% CI: 0.99–1.28).

Similar trends were also observed considering the relationships between increasing heat stress and insurance payouts, though few of results were statistically significant, such as female workers (RR: 1.33, 95% CI: 1.05–1.68), workers employed in medium-sized enterprises (RR: 1.3, 95% CI: 1.07–1.58), and workers with intermediate educational attainment (RR: 1.33, 95% CI: 1.09–1.64). Adverse trends were observed in workers with high educational attainment. With increased WBGT index, their relative risk decreased (RR: 0.79, 95% CI: 0.59–1.07), although not statistical significantly (Fig. 4).

Models with different lag periods, knots and degrees of freedom were also used as sensitivity analyses in Table S3. The results were robust according to sensitivity analyses.

4. Discussion

This is the first Chinese study quantifying work-related injuries and associated economic costs attributable to workplace heat exposure. Our findings showed that high WBGT values were associated to increased incidence of health impairments in occupational population, resulting in excessed work-related injuries and insurance payouts in Guangzhou, China.

These results partially confirm previous studies (Adam-Poupart et al., 2015; McInnes et al., 2017; Morabito et al., 2006; Sheng et al., 2018; Spector et al., 2016; Xiang et al., 2014c) which found increased injury risks with rising temperatures. However, only a few studies have quantified the fraction of work injury attributable to heat stress, and to the best of our knowledge, no study assessed the actual economic costs associated with heat- related work injuries. Xiang et al. (2018) investigated illness directly induced by heat, and found these illness only accounted for 0.1% of all injury claim, and 0.04% of total compensation costs. Martinez-Solanas et al. (2018) were the first to calculate occupational injuries attributable to ambient temperature in Spain, and found that 2.4% of occupational injuries were attributed to moderate and extreme heat conditions. In the present study, the fraction of work-related injury claims attributed to heat exposure was 4.8%, twice compared to the average value observed in Spain, but similar to results of some southern Spain provinces, those provinces have mild winters and hot summers, which is similar to the climate conditions of Guangzhou. Falling into the subtropical monsoon climate belt, Guangzhou has hot and very humid (also rainy) summer. In particular, the monthly average maximum WBGT during May to October is above 24 °C. These heat stress conditions pose adverse health effects on workers, especially for those exposed to the outdoor environment.

As for economic costs, our analysis showed that 4.1% of injury insurance compensation cost was attributed to heat stress. However, our data only contained insurance payouts, the medical fees and subsidies are only a small portion of high ambient temperature-related economic burden (Martinez-Solanas et al., 2018). Thus the economic burden of work-related injury in this research were actually underestimated, and potential costs of mental distress and productivity loss need to be taken into consideration (Takala et al., 2014).

In this study, we used the WBGT index to estimate the heat exposure of workers. The heat transfer processes of human include evaporation, convection and radiation, and these phenomena are influenced by temperature differences, humidity and wind speed. Previous studies generally used the ambient air temperature with humidity controlled (Adam-Poupart et al., 2015; McInnes et al., 2017; Xiang et al., 2014c), but the use of WBGT allows a more in-depth thermal stress analysis through the consideration of the air humidity and wind speed (and also solar radiation if available), in this way providing a complete picture of heat stress. Another advantage of using WBGT index is that it provides comparability between results and it represents an official occupational health Chinese standard "*Occupational exposure limits for hazardous agents in the workplace*" (GBZ 2.2-2007). Our results showed that in 46% of days, during the study period, the daily maximum WBGT index exceeded the recommended WBGT threshold that requires a reduction of working hours for high workload that often involve farmers, and construction workers for which preventive and protective measures are necessary.

According to the subgroup analysis, male workers underwent slightly higher injury risk than female workers, while claim costs of female workers was more influenced by high heat stress conditions.

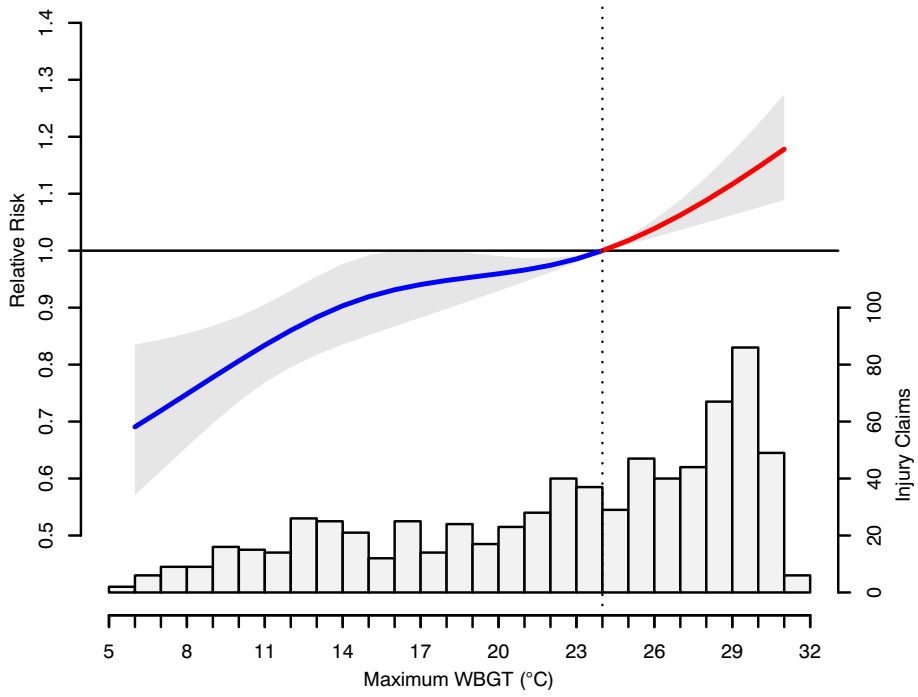


Fig. 2. The exposure-response relationship between daily maximum WBGT index and injury claims.

However, considering the large number of male workers, it is of great importance to take targeted measures to protect male workers against workplace heat stress. The higher heat-related risk of male was similar to previous studies (Adam-Poupart et al., 2015; McInnes et al., 2017; Xiang et al., 2014c), which can be explained by differences in the type and intensity of work between the genders. Men are more likely to do physically demanding jobs, and undertake jobs in harsh environment, which makes them at higher risk in hot weather. Meanwhile, physical structure differences lead to more serious consequences among injured women, as well as greater insurance payouts. Previous studies found female workers were more likely to suffer from heat stress exposure at work (Pogacar et al., 2018), with higher claim costs (Schwatka et al., 2017).

Table 2
Work-related injuries and insurance payouts attributable to heat stress above WBGT limit (25 °C).

Variables	Attributable fraction (95% eCI)	Attributable number (95% eCI)
Total	4.8 (2.9–6.9)	461 (257–658)
Gender		
Male	4.9 (2.8–7.1)	364 (208–522)
Female	4.5 (0.8–8.1)	98 (15–182)
Age group		
<35	4.7 (1.7–7.6)	201 (68–318)
35–44	5.2 (2.0–8.2)	174 (72–272)
>44	4.5 (−0.3–8.6)	87 (−3–161)
Educational attainment		
Low	4.3 (1.6–6.7)	231 (92–367)
Intermediate	6.2 (3.0–9.3)	189 (95–285)
High	3.6 (−2.2–8.9)	41 (−30–97)
Business size		
Small	5.5 (2.9–8.01)	280 (145–401)
Middle	5.2 (1.6–8.4)	152 (49–243)
Large	2.0 (−3.6–6.6)	30 (−60–100)
Injury severity		
Minor	7.7 (5.0–10.2)	348 (220–464)
Medium	1.2 (−2.7–4.7)	33 (−68–119)
Severe	4.0 (−0.2–7.8)	96 (0–184)
Insurance payout (million CNY)	4.1 (0.2–7.7)	11.58 (0.6–21.2)

Note: 95% eCI, 95% empirical confidence intervals; CNY, Chinese Yuan. 1 Chinese Yuan = 0.16 US Dollar (Exchange rate of December 31, 2012). The business size was categorized according to the Provisions on the Classification Standard for Small and Medium-sized Enterprises (No. 300 [2011]) of the Ministry of Industry and Information Technology, China.

The highest risk of heat-related work injury observed in workers with <45 years is also confirmed by recent studies (Martinez-Solanas et al., 2018; McInnes et al., 2017; Xiang et al., 2014c). Young workers are usually involved in more prolonged outdoor activities, exposing them at higher injury risk (Breslin and Smith, 2005; Fortune et al., 2013). However, the analyses which showed the increasing trends of insurance payouts were not statistically significant, suggesting larger sample size were needed to investigate effects of high heat stress.

In addition, we only observed that workers with intermediate- or low-level educational attainment were vulnerable to heat exposure. One plausible explanation is that workers with high educational attainment are more likely to work at well-equipped workplaces with air-conditioning, while workers with low educational attainment are more likely to participate in manual works, exposing them more to high heat exposure conditions and undertaking more internal heat generated by labor processes. Workers with high educational attainment may also have better awareness of health protection, so they can take more breaks and hydrate themselves better during hottest days.

Our analysis on business size indicates that workers in large enterprises seemed less likely to be affected by hot days compared with workers in small or middle enterprises, which is consistent with Xiang et al. (2014c). In general, large companies usually have improved facilities, regular safety education training and strict enforcement of labor protection. Meanwhile, the only significantly elevation of insurance payout was observed in middle-size enterprises, and this may be related to the more complete injury report system compared to small enterprises. Therefore, more attention should be paid to small- and middle-size enterprises during hot work conditions.

Results related to the injury severity suggest the highest risk for minor injuries. Minor injury usually follows neglecting and mistake, such as hitting objects or being hit by moving objects (Tawatsupa

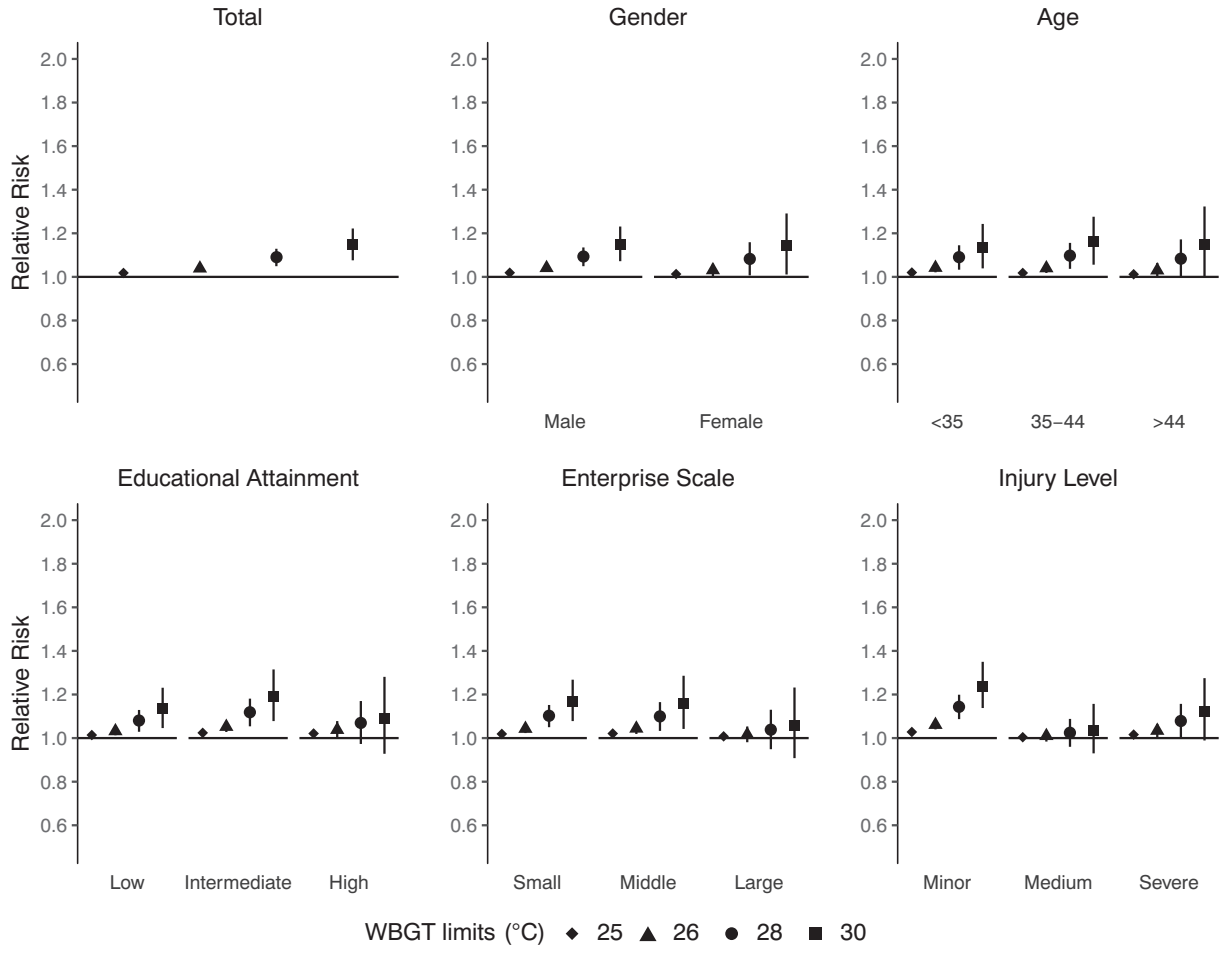


Fig. 3. Relative risks of work-related injuries at different WBGT limits. (Compared to the reference WBGT at 24 °C).

et al., 2013; Xiang et al., 2014b). These results suggest that more importance should be given to minor injuries mainly because of their increased frequency and preventability.

We found no evidence of delay effect between high WBGT index and injury claims. This is consistent with results of Xiang et al. (2014c), but different from the study of Adam-Poupart et al. (2015) which reported that heat effect on work injuries occurred two-three days after exposure. Unlike general population, workers usually have higher metabolic rate during labor works, undertake direct and immediate impacts from ambient heat (Kjellstrom et al., 2016), and their adaptive responses to the heat stress are restricted due to work duties (Gubernot et al., 2014), thus acute effect is dominant in occupational heat related injury.

Some mechanism about heat stress induced injuries have been explained (Kjellstrom et al., 2016). During hot days, the increasing body sweat represents a cooling method, which might cause dehydration, result in distraction, slow reaction, dizziness etc. (Marchetti et al., 2016). Sweaty tools and devices are harder to operate, which may lead to accidents too (Pilcher et al., 2002). Additionally, personal protective equipment (PPE) often hinders heat dissipation and increases heat strain (Gao et al., 2018). Small companies are unlikely to have complete equipment and regulations, while people at younger ages or with low educational attainment might lack experience, which can make them more vulnerable to heat stress. Other factors may also play important roles in the incidence of work-related injury, such as poor health status (Marcum et al., 2017; Spector et al., 2015), lacking of work experience (Chau et al., 2004; Foley, 2017), physical exertion (Breslin and Smith, 2005), absence of training course (Yu et al., 2017) and personal protective equipment (Chercos and Berhanu, 2017; Zhao et al., 2018), and these factors may modify the association between heat stress and work-related injury.

Over the past decade, the Chinese government has increasingly recognized heat stress as a factor of occupational hazard, and preventive measures have been taken to protect the workers' health and productivity. In the occupational health Chinese standard GBZ 2.2-2007 (MoH, 2007), jobs are divided into 4 work types based on their physical workload, and recommended work-rest schedules are provided depending on different WBGT thresholds. For example, the duration of very high workload is reduced to 6 h when the workplace WBGT reaches 26 °C. The standard of GBZ 2.2-2007 was set based on the heat stress conditions in the workplace. However, few enterprises conduct these monitoring work routinely, thus reducing the effectiveness of prevention in practice.

Increased environmental heat levels has posed severe impact to human health and global economy, and future climate change scenarios reveal that workers engaged in various parts of the world will face significant increasing of thermal stress levels. The work capacity of in-shade workers with moderate physical workload can decrease 2.04% under RCP 6.0 scenario during 2071-2099 (Kjellstrom et al., 2018), and effective measures to protect workers from injuries in the context of global warming were needed to reduce the adverse health impacts related to the increasing temperature (Xiang et al., 2014a).

Some limitations of this study should be acknowledged. Firstly, WBGT index was calculated from meteorological data (Bernard and Pourmoghani, 1999) rather than measured at workplace. With appropriate models, however, WBGT derived from standard meteorological data can express the heat stress of workplace better than single

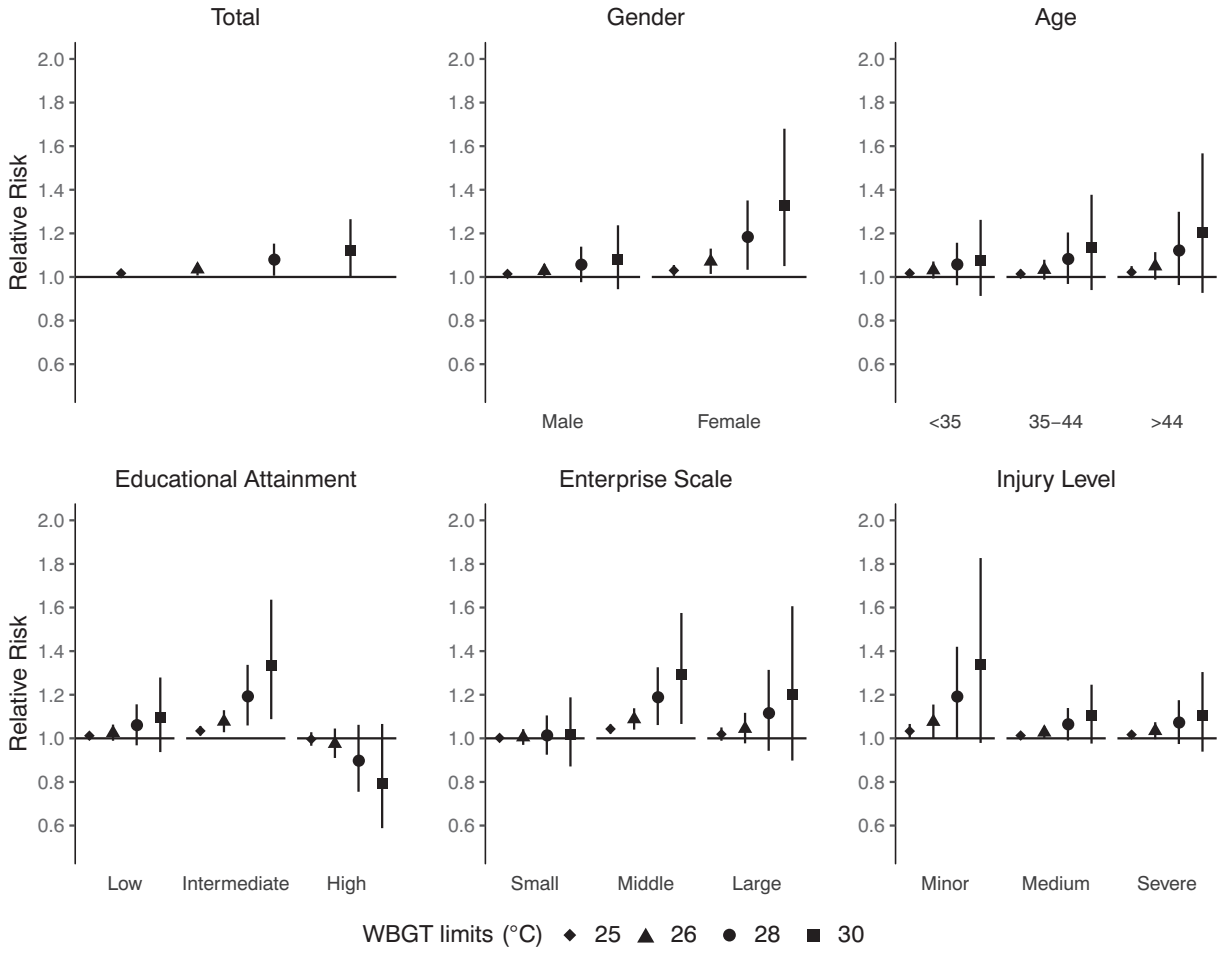


Fig. 4. Relative risks of insurance payouts at different WBGT limits. (Compared to the reference WBGT at 24 °C).

temperature indicator (Lemke and Kjellstrom, 2012). Secondly, limited coverage of work-related injury insurance is noteworthy, only 54% of workers were insured until 2012 in Guangzhou. Workers not covered by the insurance (such as migrant workers and self-employed workers) tend to have poor working conditions, and this situation may result in underestimate of heat- related injury risk and economic burden. Thirdly, detailed information such as health status, type of injury, training and job-fit was not available, and future investigation on these would provide a better understanding of heat effects on work-related injury.

In conclusion, this study showed that heat exposure significantly contributed to work-related injuries as well as economic costs in Guangzhou, China. Our findings provide an important quantitative assessment of heat effects on worker's health and insurance payouts, representing a valuable scientific basis for the development of adaptation and mitigation strategies in the light of global warming.

Acknowledgements

This work was supported by the National Key R&D Program of China [2018YFA0606201]; the Natural Science Foundation of Guangdong Province, China [2016A030313216]; and the Asia-Pacific Network for Global Change Research [CRRP2016-10MY-Huang]. The authors would like to thank Matthias Otto for developing and providing the HOTHAPS-Soft software.

Declarations of interest

The authors declare that they have no competing interests.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2019.02.201.

References

Adam-Poupart, A., Smargiassi, A., Busque, M.A., Duguay, P., Fournier, M., Zayed, J., et al., 2015. Effect of summer outdoor temperatures on work-related injuries in Quebec (Canada). Occup. Environ. Med. 72, 338–345.
Bernard, T.E., Pourmoghani, M., 1999. Prediction of workplace wet bulb global temperature. Appl. Occup. Environ. Hyg. 14, 126–134.
Breslin, F.C., Smith, P., 2005. Age-related differences in work injuries: a multivariate, population-based study. Am. J. Ind. Med. 48, 50–56.
Chau, N., Mur, J.-M., Touron, C., Benamghar, L., Dehaene, D., 2004. Correlates of occupational injuries for various jobs in railway workers: a case-control study. J. Occup. Health 46, 272–280.
Chercos, D.H., Berhanu, D., 2017. Work related injury among Saudi star agro industry workers in Gambella region, Ethiopia; a cross-sectional study. J. Occup. Med. Toxicol. 12, 7.
Foley, M., 2017. Factors underlying observed injury rate differences between temporary workers and permanent peers. Am. J. Ind. Med. 60, 841–851.
Fortune, M.K., Mustard, C.A., Etches, J.J., Chambers, A.G., 2013. Work-attributed illness arising from excess heat exposure in Ontario, 2004-2010. Can. J. Public Health 104, e420–e426.
Gao, C., Kuklane, K., Ostergren, P.O., Kjellstrom, T., 2018. Occupational heat stress assessment and protective strategies in the context of climate change. Int. J. Biometeorol. 62, 359–371.
Gasparrini, A., 2011. Distributed lag linear and non-linear models in R: the package dlnm. J. Stat. Softw. 43, 1–20.
Gasparrini, A., Leone, M., 2014. Attributable risk from distributed lag models. BMC Med. Res. Methodol. 14, 55.
Gasparrini, A., Armstrong, B., Kenward, M.G., 2010. Distributed lag non-linear models. Stat. Med. 29, 2224–2234.
Gubernot, D.M., Anderson, G.B., Hunting, K.L., 2014. The epidemiology of occupational heat exposure in the United States: a review of the literature and assessment of research needs in a changing climate. Int. J. Biometeorol. 58, 1779–1788.

Huang, C., Barnett, A.G., Wang, X., Vaneckova, P., FitzGerald, G., Tong, S., 2011. Projecting future heat-related mortality under climate change scenarios: a systematic review. Environ. Health Perspect. 119, 1681–1690.
Huang, C., Barnett, A.G., Wang, X., Tong, S., 2012. The impact of temperature on years of life lost in Brisbane, Australia. Nat. Clim. Chang. 2, 265–270.
International Organization for Standardization, 2017. ISO 7243:2017, ergonomics of the thermal environment – assessment of heat stress using the WBGT (wet bulb globe temperature) index. ISO/TC 159/SC 5 Ergonomics of the Physical Environment.
IPCC, 2018. Global warming of 1.5 °C. An IPCC Special Report on the Impacts of Global Warming of 1.5 °C Above Pre-Industrial levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty Geneva. World Meteorological Organization, Switzerland.
Kjellstrom, T., 2016. Impact of climate conditions on occupational health and related economic losses: a new feature of global and urban health in the context of climate change. Asia Pac. J. Public Health 28, 28S–37S.
Kjellstrom, T., Lemke, B., Matthias Otto, P., Hyatt, O.M., Briggs, D.J., Freyberg, C.A., 2015. Heat impacts on work, human performance, and daily life. Climate Change and Public Health, pp. 73–86.
Kjellstrom, T., Briggs, D., Freyberg, C., Lemke, B., Otto, M., Hyatt, O., 2016. Heat, human performance, and occupational health: a key issue for the assessment of global climate change impacts. Annu. Rev. Public Health 37, 97–112.
Kjellstrom, T., Freyberg, C., Lemke, B., Otto, M., Briggs, D., 2018. Estimating population heat exposure and impacts on working people in conjunction with climate change. Int. J. Biometeorol. 62, 291–306.
Lemke, B., Kjellstrom, T., 2012. Calculating workplace WBGT from meteorological data: a tool for climate change assessment. Ind. Health 50, 267–278.
Li, M., Gu, S., Bi, P., Yang, J., Liu, Q., 2015. Heat waves and morbidity: current knowledge and further direction-a comprehensive literature review. Int. J. Environ. Res. Public Health 12, 5256–5283.
Liljegren, J.C., Carhart, R.A., Lawday, P., Tschopp, S., Sharp, R., 2008. Modeling the wet bulb globe temperature using standard meteorological measurements. J. Occup. Environ. Hyg. 5, 645–655.
Mairiaux, P., Malchaire, J., 1985. Workers self-pacing in hot conditions: a case study. Appl. Ergon. 16, 85–90.
Marchetti, E., Capone, P., Freda, D., 2016. Climate change impact on microclimate of work environment related to occupational health and productivity. Ann. Ist. Super. Sanita 52, 338–342.
Marcum, J.L., Chin, B., Anderson, N.J., Bonauto, D.K., 2017. Self-reported work-related injury or illness - Washington, 2011–2014. MMWR Morb. Mortal. Wkly Rep. 66, 302–306.
Martinez-Solanas, E., Lopez-Ruiz, M., Wellenius, G.A., Gasparrini, A., Sunyer, J., Benavides, F.G., et al., 2018. Evaluation of the impact of ambient temperatures on occupational injuries in Spain. Environ. Health Perspect. 126, 067002.
McInnes, J.A., Akram, M., MacFarlane, E.M., Keegel, T., Sim, M.R., Smith, P., 2017. Association between high ambient temperature and acute work-related injury: a case-crossover analysis using workers' compensation claims data. Scand. J. Work Environ. Health 43, 86–94.
Minister of Health of the People's Republic of China, 2007. GBZ 2.2-2007, Occupational Exposure Limits for Hazardous Agents in the Workplace. Part2: Phisical Agents. http://www.xjwsjd.gov.cn/wsbz/zywsbz/6035.htm, Accessed date: 16 October 2018.
Ministry of Labor and Social Security of the People's Republic of China, 2006. Ministry of Health of the People's Republic of China. GB/T 16180-2006, Standard for Identify Work Ability - Gradation of Disability Caused by Work-Related Injuries and Occupational Diseases. http://szsi.sz.gov.cn/xzzq/bzgf/200811/P020131121615210349353.doc, Accessed date: 16 October 2018.
Morabito, M., Cecchi, L., Crisci, A., Modesti, P.A., Orlandini, S., 2006. Relationship between work-related accidents and hot weather conditions in Tuscany (Central Italy). Ind. Health 44, 458–464.
Odame, E.A., Li, Y., Zheng, S., Vaidyanathan, A., Silver, K., 2018. Assessing heat-related mortality risks among rural populations: a systematic review and meta-analysis of epidemiological evidence. Int. J. Environ. Res. Public Health 15.
Otto, M., Lemke, B., Kjellstrom, T., 2014. Hothaps-soft: a tool for the estimation and analysis of local climate and population heat exposure. http://www.climatechip.org/hothaps-software, Accessed date: 16 October 2018.
Pilcher, J.J., Nadler, E., Busch, C., 2002. Effects of hot and cold temperature exposure on performance: a meta-analytic review. Ergonomics 45, 682–698.
Pogacar, T., Casanueva, A., Kozjek, K., Ciuha, U., Mekjavic, I.B., Kajfez Bogataj, L., et al., 2018. The effect of hot days on occupational heat stress in the manufacturing industry: implications for workers' well-being and productivity. Int. J. Biometeorol. 62, 1251–1264.
R Core Team, 2018. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria.
Schulte, P.A., Bhattacharya, A., Butler, C.R., Chun, H.K., Jacklitsch, B., Jacobs, T., et al., 2016. Advancing the framework for considering the effects of climate change on worker safety and health. J. Occup. Environ. Hyg. 13, 847–865.
Schwatka, N.V., Atherly, A., Dally, M.J., Fang, H., vSB, C., Tenney, L., et al., 2017. Health risk factors as predictors of workers' compensation claim occurrence and cost. Occup. Environ. Med. 74, 14–23.
Sheng, R., Li, C., Wang, Q., Yang, L., Bao, J., Wang, K., et al., 2018. Does hot weather affect work-related injury? A case-crossover study in Guangzhou, China. Int. J. Hyg. Environ. Health 221, 423–428.
Smith, C.J., Johnson, J.M., 2016. Responses to hyperthermia. Optimizing heat dissipation by convection and evaporation: neural control of skin blood flow and sweating in humans. Auton. Neurosci. 196, 25–36.
Spector, J.T., Krenz, J., Blank, K.N., 2015. Risk factors for heat-related illness in Washington crop workers. J. Agromedicine 20, 349–359.
Spector, J.T., Bonauto, D.K., Sheppard, L., Busch-Isaksen, T., Calkins, M., Adams, D., et al., 2016. A case-crossover study of heat exposure and injury risk in outdoor agricultural workers. PLoS One 11, e0164498.
Takakura, Jy, Fujimori, S., Takahashi, K., Hijioka, Y., Hasegawa, T., Honda, Y., et al., 2017. Cost of preventing workplace heat-related illness through worker breaks and the benefit of climate-change mitigation. Environ. Res. Lett. 12.
Takala, J., Hamalainen, P., Saarela, K.L., Yun, L.Y., Manickam, K., Jin, T.W., et al., 2014. Global estimates of the burden of injury and illness at work in 2012. J. Occup. Environ. Hyg. 11, 326–337.
Tawatsupa, B., Yiengprugsawan, V., Kjellstrom, T., Berecki-Gisolf, J., Seubsman, S.-A., Sleigh, A., 2013. Association between heat stress and occupational injury among Thai workers: findings of the Thai Cohort Study. Ind. Health 51, 34–46.
Vanos, J.K., Warland, J.S., Gillespie, T.J., Kenny, N.A., 2010. Review of the physiology of human thermal comfort while exercising in urban landscapes and implications for bioclimatic design. Int. J. Biometeorol. 54, 319–334.
Xia, Y., Li, Y., Guan, D., Tinoco, D.M., Xia, J., Yan, Z., et al., 2018. Assessment of the economic impacts of heat waves: a case study of Nanjing, China. J. Clean. Prod. 171, 811–819.
Xiang, J., Bi, P., Pisaniello, D., Hansen, A., 2014a. Health impacts of workplace heat exposure: an epidemiological review. Ind. Health 52, 91–101.
Xiang, J., Bi, P., Pisaniello, D., Hansen, A., 2014b. The impact of heatwaves on workers' health and safety in Adelaide, South Australia. Environ. Res. 133, 90–95.
Xiang, J., Bi, P., Pisaniello, D., Hansen, A., Sullivan, T., 2014c. Association between high temperature and work-related injuries in Adelaide, South Australia, 2001–2010. Occup. Environ. Med. 71, 246–252.
Xiang, J., Hansen, A., Pisaniello, D., Dear, K., Bi, P., 2018. Correlates of occupational heat-induced illness costs: case study of South Australia 2000 to 2014. J. Occup. Environ. Med. 60, e463–e469.
Ye, X., Wolff, R., Yu, W., Vaneckova, P., Pan, X., Tong, S., 2012. Ambient temperature and morbidity: a review of epidemiological evidence. Environ. Health Perspect. 120, 19–28.
Yu, W., Mengersen, K., Wang, X., Ye, X., Guo, Y., Pan, X., et al., 2012. Daily average temperature and mortality among the elderly: a meta-analysis and systematic review of epidemiological evidence. Int. J. Biometeorol. 56, 569–581.
Yu, I.T., Yu, W., Li, Z., Qiu, H., Wan, S., Xie, S., et al., 2017. Effectiveness of Participatory Training in Preventing Accidental Occupational Injuries: a Randomized-Controlled Trial in China. pp. 226–233.
Zander, K.K., Botzen, W.J.W., Oppermann, E., Kjellstrom, T., Garnett, S.T., 2015. Heat stress causes substantial labour productivity loss in Australia. Nat. Clim. Chang. 5, 647–651.
Zhao, Y., Yi, W., Chan, A.P.C., Wong, D.P., 2018. Impacts of cooling intervention on the heat strain attenuation of construction workers. Int. J. Biometeorol. 62, 1625–1634.